

Resolution of the Solar Neutrino Anomaly

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Abstract

The solar neutrino anomaly, measurements discrepant from predictions of the Standard Solar Model, has existed for over 30 years. Multiple experiments measuring fluxes from several reactions in the hydrogen fusion chain have added to the puzzle. Each of the several elements of the enigma are resolved by recognition of measurements establishing that most of the sun's fusion must occur near the surface rather than the core.

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THE ENIGMA – Five elements presently comprise the solar neutrino puzzle; all consequences of divergence between Standard Solar Model (SSM) prediction and measured data: 1) neutrino detection shortfall; 2) neutrino solar cycle variation; 3) two neutrino detectors with discrepant results; 4) neutrino surges coinciding with major solar flares, and 5) absence of a measurable ^7Be neutrino flux. All present measurements are consistent with near surface fusion and require no new physics nor assumed neutrino properties.

Initial results of the first substantial solar neutrino detector [1] showed the flux well below the SSM predicted value. While later theory changes reduced the discrepancy from $\frac{1}{10}$ to $\frac{1}{3}$, the difference remains beyond uncertainties [2]. In consequence, that radio-chemical ^{37}Cl Homestake experiment remains under scrutiny. Others, existent and planned, seek to further the study [3]. The Kamiokande Čerenkov “telescope” is sensitive to only higher energy neutrinos [4], while two radio-chemical ^{71}Ga experiments, SAGE [5] and GALLEX [6] are able to detect comparatively low energy neutrinos. All have measured neutrino fluxes substantially below expectation. Recently SAGE reported [7] a mean since 1990 start-up of 73 solar neutrino units (SNU), while GALLEX reduced their mean since 1991 start-up, 87 SNU earlier [8] to 77 SNU [9]. Solar neutrino data are averaged as accepted theory forbids variance in times less than 10 million years [2]. SAGE and GALLEX measurements, dominated by neutrinos from the fundamental proton-proton (PP) fusion reaction (Fig. 1), are $\sim 60\%$ of prediction. Both GALLEX [9] and SAGE [7] report the flux below the predicted [10] level of 79 SNU (Fig. 2) at which the sun is fusing the minimum amount of hydrogen required for its radiation. Mean for both is currently 75 ± 7 SNU.

The second element is a reported ~ 11 year variation of the Homestake measured neutrino flux anti-correlated with sunspot number [11]. Neutrino capture produces only ~ 0.5 radioactive ^{37}Ar atom/day, hence individual measurements fluctuate ($1\sigma \approx 30\%$). With solar gravitational and luminosity time constants $\sim 10^7$ and nuclear $\sim 10^{10}$ years, SSM prohibits short period variation, with reported changes attributed to statistical scatter abetted by analysis procedures [12].

The third element is an apparent discrepancy between Homestake results ($\sim 35\%$ of SSM), believed dominated by neutrinos from ^8B (Fig. 1) and Kamiokande ($\sim 50\%$ of SSM) that should measure, almost exclusively, the same ^8B neutrinos. Davis [13], has already shown that the difference disappears if only contemporaneous acquired data are compared.

The fourth element involves neutrino flux increases noted in Homestake results coinciding with major solar flares [14]. These surges (SSM incompatible) are explained as statistical fluctuation or cosmic ray produced [2]. Computer simulations show the $^{37}\text{Cl}(\nu, e^-)^{37}\text{Ar}$ detection rate of ~ 1.2 atoms/day associated with flares relative to a mean of 0.5 atoms/day can be expected statistically in several percent of the runs [13].

The correlation between a great solar flare and Homestake neutrino enhancement was tested in 1991. Six major flares occurred from May 25 to June 15 including the great June 4 flare associated with a coronal mass ejection and production of the strongest interplanetary shock wave ever recorded (later detected from spacecraft at 34, 35, 48, and 53 AU) [15]. It also caused the largest and most persistent (several months) signal ever detected by terrestrial cosmic ray neutron monitors in 30 years of operation [16]. The Homestake exposure (June 1–7) measured a mean ^{37}Ar production rate of 3.2 ± 1.5 atoms/day (≈ 19 ^{37}Ar atoms produced in 6 days) [13]; about 5 times the rate of ≈ 0.65 day $^{-1}$ for the preceding and following runs, > 6 times the long term mean of ≈ 0.5 day $^{-1}$ and $> 2\frac{1}{2}$ times the highest

rates recorded in ~ 25 operating years. Attributing this burst (SSM forbidden) that dwarfed the background neutrino flux to statistical variation stretches probability when it coincides with the largest recorded flare.

The fifth element has been termed [17] a “paradox.” Kamiokande results are about 50% of the predicted [18] ^8B neutrino flux [4]. Applying that percentage to the SSM prediction of 7.9 SNU for Homestake exceeds their mean of 2.55 ± 0.25 SNU [3] leaving no room for ^7Be neutrino detections (Table I). Results from both GALLEX [9] and SAGE [7] below the predicted PP neutrino flux (almost model independent) also leave no room for a ^7Be neutrino flux. As ^8B results from ^7Be (Fig. 1), measuring neutrinos from the daughter reaction while absents those from the parent is paradoxical.

Revised “Mikheyev-Smirnov-Wolfenstein (MSW)” neutrino physics [19] explains the discrepancy between SSM prediction and observation (Table I) by hypothetical neutrino flavor changes. Measurement has excluded almost all possible MSW “solutions.” Several ad hoc non-standard solar models that mix various fractions of the core continuously or episodically [20] represent other efforts to match measurement. If the data are accepted, invented physics models cannot explain neutrino surges with flares and/or solar activity variation.

The solar neutrino puzzle is the SSM conflicting with observation! After summarizing a set of measurements that show most (all?) solar fusion occurring near the surface (contradicting a fundamental SSM assumption), we present our near surface fusion interpretation that resolves *all* aspects of the solar neutrino puzzle.

^7Be IN EARTH ORBIT REQUIRES FUSION NEAR THE SUN’S SURFACE – Two independent teams measured ^7Be on the leading surfaces of the Long Duration Exposure Facility (LDEF), retrieved after orbiting the Earth for 69 months [21]. The concentration necessary to account for the measurements was several orders of magnitude greater in orbit than in the stratosphere ~ 300 km below. In the troposphere and stratosphere, radioactive ^7Be (53 day half-life) is accepted as the consequence of high energy cosmic ray spallation of nitrogen and oxygen mostly between 15 and 20 km [22]. With orbit altitude production inconsequential, a fast vertical transport and concentration mechanism was sought. To bolster that hypothesis, pieces of LDEF were examined for ^{10}Be , a radioisotope with a 1.5 million year half-life, similar chemistry, spallation production and transport likelihood. Unexpected, the only ^{10}Be found was inherent in the aluminum, as about the same was found on interior and control surfaces and it did not exhibit the ^7Be 100 times leading to trailing surface excess [23]. This makes cosmic ray spallation a most improbable source.

Fusion is the remaining method to produce ^7Be with the sun the sole source consistent with known astrophysics. Further, the half-life only permits the ^7Be to originate near the surface, as SSM tables [2] show core fusion 10^{19} short of providing an adequate amount for the LDEF measurements. Solar luminosity requires $4[10]^{38}$ protons fused per second. If PPII branching is $\sim 10\%$, this yields $5[10]^{36}$ ^7Be nuclei per second. If about 10^{-4} of this joins the solar wind, it provides $\sim 5[10]^{32}$ nuclei/s. The escaping fraction may be contested $10^{\pm 2}$ without altering the conclusion. This produces a flux at Earth of $\sim 2[10]^9 \text{ atoms} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$. The Earth’s bow shock is a formidable barrier to the solar wind [24], so we estimate penetration of $\sim 10^{-3}$. Allowing for in-flight decay, we obtain an influx of $\sim 10^{6\pm 3} \text{m}^{-2} \cdot \text{s}^{-1}$ of ^7Be atoms. Rather than estimate velocity and density, we take this flux impinging directly on the LDEF leading surface. If $\sim 10^{-3}$ atoms stick, then we may approximate the equilibrium concentration by $\sim 10^3 \text{m}^{-2} \cdot \text{s}^{-1}$ times the 53 day half-life or $\sim 5[10]^9 \text{m}^{-2}$ as reported [21],

with our computation having $\sim 10^{\pm 4}$ uncertainty.

Surface fusion is no longer bizarre since the 2.2 MeV gamma ray line of the $P(n,\gamma)D$ reaction was observed [25] during the solar flare of May 24 1990. Why would DP fusion in flares not supply a sufficient flux of ${}^7\text{Be}$ atoms? The flux estimated above would have to be reduced by $\sim 10^4$ for the solar deuterium/hydrogen ratio and an additional factor of $\geq 10^3$ as major flares occur only several times per year even near the peak of the solar cycle. Hence, if only flare production is invoked for the ${}^7\text{Be}$, a shortfall $\geq 1,000$ results relative to the LDEF measurement. Another method of quantifying this flare shortfall is to equate our low uncertainty to the deuterium/hydrogen ratio. Then the ratio of flare radiance to solar luminosity is the amount by which flare fusion fails to account for the LDEF measurement. The ${}^{10}\text{Be}$ experiment [23] eliminating a terrestrial source also rules out significant solar cosmic ray spallation production. Thus, two independent measurements with high signal to noise (shown by the 100 to 1 leading/trailing surface ratio), establish that *PP chain fusion near the solar surface is the sole source capable of providing the requisite flux* but say naught about the fusion process.

RESOLUTION OF THE NEUTRINO ANOMALY – With most (all?) fusion near the surface, many core premises of the SSM, e.g., long term parametric stability, are invalid. With fusion a temporal and spatial variable, changes in isotopic-chemical fractions, temperature and pressure must cause variable branching. Observation indicates that they are within several multiples of SSM values.

Solar cycle variation of temperature and composition [26] permits us to explain neutrino measurements. Once formed, three possibilities exist for ${}^7\text{Be}$; 1) electron capture, 2) proton capture or 3) departure in the solar wind. During solar maximum, UV, EUV and x-ray luminosity increase dramatically, indicative of a substantial increase in high energy electrons. This enhances PP_{II} reactions increasing ${}^7\text{Be}$ neutrinos. If PP_{II} goes to completion by electron capture (Fig. 1) and a small fraction is lost to the solar wind, fewer ${}^7\text{Be}$ nuclei are available for PP_{III} proton capture. Further, the additional ${}^7\text{Li}$ produced competes with ${}^7\text{Be}$ for proton capture, assuring less ${}^8\text{B}$. With electron capture favored $\sim 10^3$ over proton capture, we are discussing only the tail of the distribution. However, if the high energy electron density increases, producing more ${}^7\text{Li}$, and the solar wind rises, then the flux of ${}^8\text{B}$ neutrinos must decrease appreciably. This theoretically dominates Homestake measurement and is substantially all that Kamiokande can detect. Such an anti-correlation with sunspot number was reported [11]. This results in a ${}^7\text{Be}$ neutrino flux that follows the solar cycle, anti-correlated with ${}^8\text{B}$ neutrinos. The neutrino energy dependence of ${}^{37}\text{Cl}$ capture heavily weights ${}^8\text{B}$ neutrino detections in Homestake data (Table I), indicating why nearly simultaneous measurements must be used to compare Homestake with Kamiokande [13].

Measurement shows that PP fusion is enhanced during major flares and branching should vary significantly. While Kamiokande data may vary with the solar cycle [13], it is unclear whether real time Kamiokande ${}^8\text{B}$ neutrino detections increased during the 1991 activity. Apart from absence of reports, our uncertainty stems from the reduced ${}^8\text{B}$ neutrino flux measured during solar maxima. It is possible for a fusion burst, while multiplying the ${}^7\text{Be}$ neutrino flux, to leave unchanged or even reduce ${}^8\text{B}$ neutrinos.

The missing ${}^7\text{Be}$ “paradox” results from assuming an invariant neutrino flux [18]. LDEF and solar spectral observations attest to an adequate ${}^7\text{Be}$ supply. In showing contempo-

aneous consistency with Kamiokande, Davis [13] reduced Homestake detections by 0.77 (Table I) to compute the ^8B flux, leaving room for a ^7Be component. The “missing ^7Be ” component of recently reported SAGE and GALLEX values are due to currently reduced solar fusion and should get even lower when solar minimum data are added before beginning to again rise (if GALLEX continues).

SUMMARY AND DISCUSSION – The five elements presently comprising the solar neutrino problem: 1) neutrino shortfall; 2) neutrino solar cycle variation; 3) the Homestake Kamiokande discrepancy; 4) neutrino surges coinciding with major solar flares; 5) absence of ^7Be neutrinos; measurements that diverge from prediction show the SSM flawed. Each may be resolved with known physics recognizing the entire PP fusion chain occurs near the solar surface. The shortfall relative to SSM prediction results from the core (fusion) assumption of long term invariance and its concomitant effect upon branching. Changes in ^3He (PPII) and energetic electron concentrations (PPIII), observed on the active sun, cause variable branching resulting in the Homestake solar cycle anti-correlation. The PP and ^7Be neutrino flux correlate with sunspot number showing varying fusion. Enhanced PPII terminations and solar wind loss reduce ^8B production, causing the PPIII neutrino flux to change inverse to solar activity. While the ^8B neutrino flux is about three orders of magnitude less than from ^7Be (Table I), detection by ^{37}Cl is near comparable due to the large neutrino energy dependence. Hence, we conclude that the Homestake detections of ^7Be neutrinos relative to ^8B detections vary with solar activity. While the Homestake Kamiokande “discrepancy” has been resolved [13], long term comparison of data should establish this difference in the two neutrino fluxes.

Bursts of neutrino detections recorded during active solar periods are the consequence of multiplied near surface PP fusion during coronal mass ejections and associated major solar flares. These spikes are substantial in Homestake, and may have been detected by GALLEX and SAGE during the 1991 active period. Variation of Homestake data with sunspot number is significant and indicates cycling near surface fusion rates. Changes in GALLEX and (allowing for start-up problems) in SAGE, are consistent with solar cycle variation of PP surface fusion, contradicting the SSM.

In summation, present measurements give no credence to fusion occurring in the core region of the sun and therefore, stars in general. Commonly observed large and short period stellar luminosity variations also support fusion near the stellar surface.

Noteworthy is that the foregoing is independent of neutrino mass and magnetic moment. Other non-standard models generally address one aspect of the anomaly, e.g., the deficient flux. This near surface fusion solution is unique in respecting all measurements and in particular recognizing the significance of the LDEF $^7\text{Be} - ^{10}\text{Be}$ results. A serious criticism must supply an alternative to fusion near the solar surface as the ^7Be source. Beyond the limits of this communication is discussion of near surface (below excepting major flares), non equilibrium fusion mechanics, a subject of future papers.

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FIGURES

FIG. 1. Principle reactions, approximate Standard Solar Model branching (relative to 100% proton-proton combinations) and designations for the solar hydrogen to helium fusion chain.

FIG. 2. Chronology of GALLEX and SAGE reported results. Early SAGE points are for the time periods indicated by horizontal bars, while all GALLEX points are means since 1991 startup. Errors shown are statistical and systematic added quadratically. At the upper right is shown the range of predictions of derivations from the Standard Solar Model (closed bar) with their 1σ error extensions (open bars). The horizontal line is the theoretically computed minimal solar model below which there is insufficient hydrogen fusion to power the solar luminosity [10]. Early low values reported by the SAGE consortium, believed to result from start-up difficulties, were subsequently revised upward [7].

TABLES

TABLE I. Standard Solar Model neutrino predictions [18] and measurements [3] compared.

ν Source Reaction	Branching Ratio	ν energy (MeV)	ν flux ($\text{m}^{-2}\text{s}^{-1}$)	Homestake $^{37}\text{Cl}^{\text{a}}$ (SNU)	SAGE & GALLEX $^{71}\text{Ga}^{\text{a}}$ (SNU)	Kamiokande 7.5 MeV cut $^8\text{B } \phi^{\text{b}}$ ($10^{-2}\text{m}^{-2}\text{s}^{-1}$)
PP	$\sim 100\%$	0 – 0.420 spectrum	$6.0[10]^{14}$	0	71	0
^7Be	13%	0.861 line (90%) 0.383 line (10%)	$4.7[10]^{13}$	1.1	34	0
^8B	0.017%	0 – 14.1 spectrum	$5.8[10]^{10}$	6.1	14	5.7
Total ^c				7.9	132	5.7
Measured				2.55 ± 0.25	75 ± 7	2.9 ± 0.4

^aThreshold for $^{37}\text{Cl}(\nu, e^-)^{37}\text{Ar}$ is 0.814 MeV and for $^{71}\text{Ga}(\nu, e^-)^{71}\text{Ge}$ is 0.233 MeV.

^bAs the SNU refers to captures, fluxes are listed for the Kamiokande electron scatter Čerenkov detector.

^cAs only principle solar hydrogen fusion reactions are listed, totals are larger than the sum of the values shown.



